2007

Is Yellowstone Losing Its Steam?— Chloride Flux Out of Yellowstone National Park

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By Irving Friedman and Daniel R. Norton

Chapter I *of*

Integrated Geoscience Studies in the Greater Yellowstone Area—Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem

Edited by Lisa A. Morgan

Professional Paper 1717

U.S. Department of the Interior
U.S. Geological Survey

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Is Yellowstone Losing Its Steam?— Chloride Flux Out of Yellowstone National Park

By Irving Friedman[1] and Daniel R. Norton[2]

Abstract

Chloride flux, a surrogate for heat flow, was determined for the four rivers draining Yellowstone National Park (the Park) for the water years (October 1 through September 30) 1983 through 2003, with the exception of 1995 and 1996. The chloride emitted by the geothermal system underlying Yellowstone Park is designated "thermal chloride," and it constitutes 94 percent of the total chloride exiting the Park. The remainder of the chloride is contributed by rainfall, rock weathering, and a minor amount due to human impact.

Of this 94 percent, the Fall, Madison, Snake, and Yellowstone Rivers have been determined to discharge 93 percent of the chloride leaving the Park; the remaining 7 percent exits along the west boundary into the Henrys Fork River. The chloride flux for each river varied seasonally and annually, and we postulate that it depended primarily on the flow of hot springs. This flow, in turn, depended on the height of the local water table, which increased during spring runoff and varied annually in synchronism with changes in precipitation.

The sum of the annual chloride fluxes for the four rivers varies as much as 20 percent year-to-year. This sum, when corrected for the climatic factors, shows a decline of 10 percent during the past 20 years. A lengthening in the period between eruptions of Old Faithful Geyser has also been observed. We believe that these changes may be related to deflation of the Yellowstone caldera documented by changes in ground levels surrounding Yellowstone Lake.

Acknowledgments

We thank John Varley, Director, Center for Resources, Yellowstone National Park, for financial aid and encouragement. We are especially indebted to Jake Jacobson, Chief, Idaho Falls field office, USGS, who was responsible for establishment of stream gages on the Fall River when diversion of the river for power generation impacted the accuracy of measurements at the historic river-gaging site and provided assistance in collecting data from remote sites. Dale Swanson, Fremont-Madison Water District (Ashton, Idaho), provided discharge data for the irrigation canals that diverted water from the Fall River. The Ida-West Energy Company (Boise, Idaho) provided data on the power generated by diversion of the Fall River water through the Marysville Canal. Ron Shields, Montana District, U.S. Geological Survey (USGS), was very helpful in our study of the Yellowstone and Madison River drainages. Gary Cottrell, USGS National Water Quality Laboratory, was of great assistance in the chloride analysis. The late Rick Hutchinson, Yellowstone National Park geologist, provided great service in the field and acted as coordinator for the sample collectors. Unpublished data on the frequency of eruptions of Old Faithful was furnished by Rick Hutchison and Tom Hougham, Yellowstone National Park. Funding for this research was provided by both the National Park Service and the U.S. Geological Survey.

Introduction

The heart of the Yellowstone National Park (the Park) ecosystem resides in the thermal flux generated by a magma body under the Park. This heat flux manifests itself in the many geysers and hot springs that are the features that originally caused the region to be set aside as the world's first national park. This report discusses an attempt to monitor the state of the thermal flux in the Park and to relate changes in the flux to changes in other aspects of the ecosystem.

Direct measurements of thermal flux or heat flow are difficult to determine. Chloride flux, which is more easily determined, has been used as a surrogate for heat flow (Ellis and Wilson, 1955; Fournier and others, 1976; Norton and Friedman, 1985; Friedman and Norton, 1990; Norton and Friedman, 1991; Friedman and others, 1993).

Norton and Friedman (1985) determined that 94 percent of the chloride exiting Yellowstone is from the geothermal system. The remainder of the chloride is derived from the atmosphere, low-temperature rock weathering, subsurface leaching of rocks, and human waste.

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The rationale for previous investigations varied from purely scientific objectives to the practical need to establish baseline data to assess adverse impacts on thermal features of the Park from proposed commercial development of water, geothermal, oil, and gas resources adjacent to Yellowstone. Those investigations have been used to relate temporal changes in the plumbing system that connects the magmatic reservoir to changes in the shallow hydrothermal systems underlying Yellowstone. This report extends the investigation of Norton and Friedman (1985) of the chloride flux leaving the Park via four major rivers: Fall, Madison, Snake, and Yellowstone. The chloride flux exiting the Park was estimated to be 94 percent of the total flux—the remainder exiting along the west boundary of the Park in the Henrys Fork drainage (Norton and Friedman, 1985; Friedman and others, 1993).

This study, a cooperative effort between the U.S. Geological Survey (USGS) and the National Park Service (NPS), includes data for water years (WY) 1982–1989, published by Norton and Friedman (1991). The data for WY 1982–1989 have been recalculated using improved protocols, and they are included with data acquired for WY 1990–2003. No samples were collected during WY 1995 and 1996. Collection resumed in WY 1997.

Definition of Water Year

All reported values of annual data, with the exception of figure 12, are calculated for the water year (WY) defined as 12 months beginning on October l and ending on September 30. In figure 12 the data are given for the calendar year.

Site Descriptions

The locations of stream-gaging sites are shown in figure 1, and the site descriptions are listed in table 1. All of the sites are USGS gaging stations. Sites for discharge measurements were selected on the Fall, Madison, Snake, and Yellowstone Rivers where the rivers exit the Park. The Madison River was gaged from September 1982 to October l986, and from 1990 through 2003. For the 3 years that the Madison River site was inoperative, we used data from stations on the Firehole and Gibbon Rivers, which converge to become the Madison, to calculate discharge and chloride flux for the Madison River.

Water samples for chloride analysis were collected at the gaging sites (fig.1) with the exception of the Yellowstone River samples. To exclude chloride input from La Duke Hot Spring, which is outside the Park and discharges into the river 3.2 km upstream from the gaging site, also outside the Park, the Yellowstone River water samples were collected l km upstream from where the hot-spring water enters the river.

Experimental Results

Chloride Analysis

For WY 1983 through 1989, chloride determinations were made by a modification of the thiocyanate-spectrophotometric method of Skoustad and others (1979), in which an automated segmented-sample analyzer replaced the discrete-sample analyzer. To increase the accuracy of the method, we introduced our chloride standard solutions between every 10 to 15 samples. The laboratory results were normalized against these standards, which were prepared gravimetrically from pure NaCl. This resulted in an accuracy of ±2 percent.

For WY 1990 through 2003, chloride concentrations were determined utilizing an ion chromatography method described by Fishman and Friedman (1989). A series of gravimetrically prepared KCl standard solutions were inserted at the beginning, middle, and end of each group of 20 samples, and the laboratory results were normalized to those standards. The digital readout of the automated chloride-analysis apparatus limited the precision of the method. The precision varied from 1 percent relative standard deviation for chloride concentrations higher than 50 ppm, to 3 percent for concentrations lower than 10 ppm. Prior to 2000, the National Water Quality Laboratory of the USGS made all of the chloride analyses. After 2000 the analyses were made by the USGS Volcano Hazards Laboratory in Menlo Park, Calif.

Stream Discharge Measurements and Sampling

The river discharge and chloride concentration data were published by Friedman and Norton (2000). That publication shows plots of river discharge and chloride concentration.

Discharge measurements were obtained from the Water Resources Division (WRD) of the USGS, which used standard hydrologic methods and automated recorders. Their methods are described in standard textbooks, in Carter and Davidian (1968), in Rantz (1982), and are reported to have an accuracy of ±5 percent.

The water samples for chloride analyses were collected with 50-mL plastic syringes. They were filtered on-site through 5-µm membrane filters into plastic bottles before submittal to the WRD National Water Quality Laboratory in Denver, Colo., for analysis. The 5-µm filter was chosen because it is the smallest porosity filter that could be used without becoming plugged by solids that were present in the water. Beginning in 2001, a 0.4-µm filter was used.

Our schedule for water sampling of the rivers was monthly for January, February, November, and December; bi-monthly for March, April, September, and October; and weekly for May, June, July, and August. The 28-sample

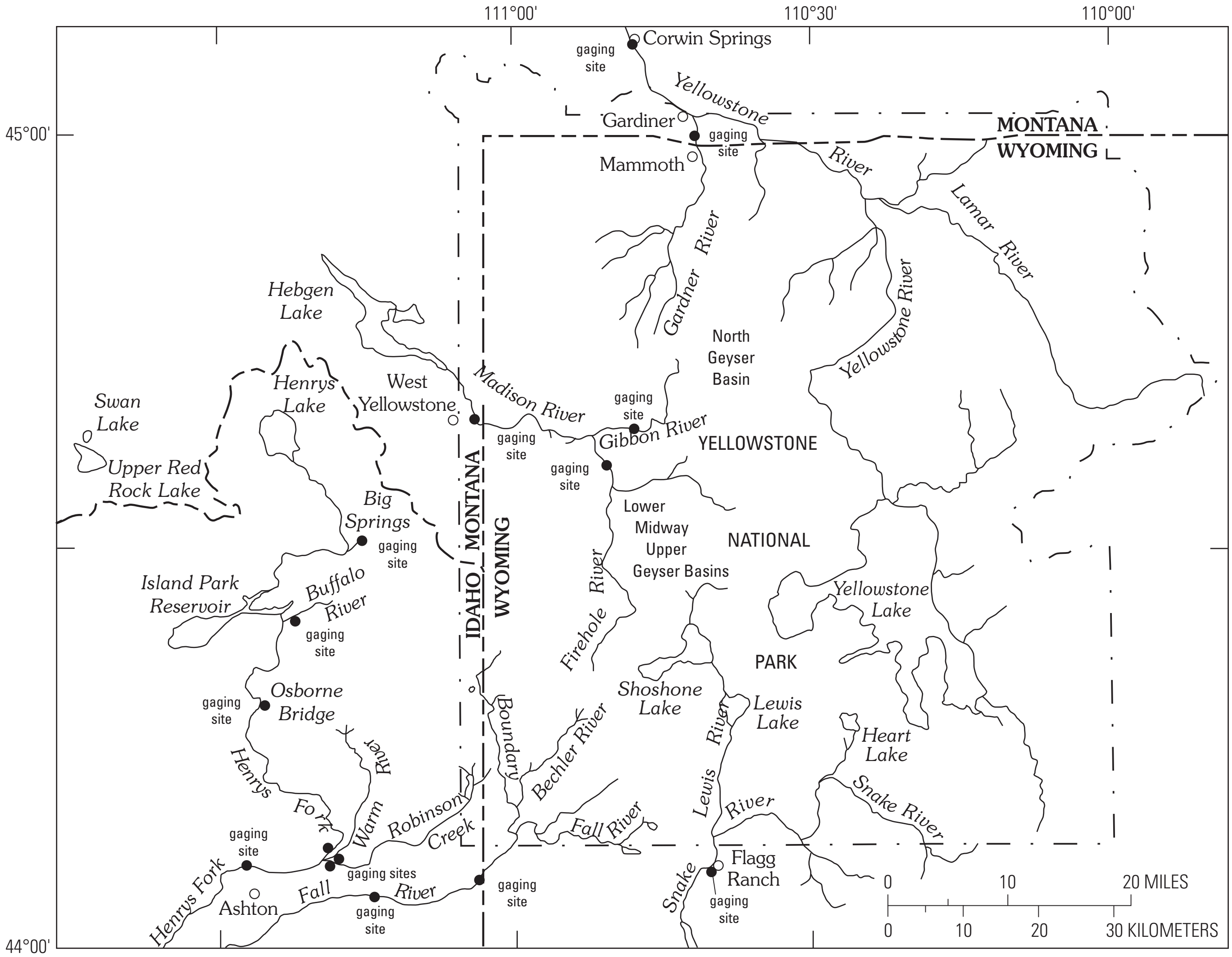

Figure 1. Map showing stream-gaging stations.

protocol resulted in greater accuracy than the normal WRD sampling protocol, particularly during the period of high runoff in the spring and summer. The usual water-sampling protocol used by WRD is to collect a sample at each site every 6 weeks. Using data from both sampling protocols, we calculated the annual chloride flux for 1985 and 1986 for the four major rivers that drain the Park. The flux calculated for individual rivers by the two protocols differs by as much as 12 percent. The discrepancy depends on the specific dates of sampling as related to the timing of snowmelt runoff. In view of those results, we designed our sampling schedule to include additional sampling during the period of high discharge. To the 28 samples per year for each site that we collected, we added some of the 9 samples collected by the WRD.

In WY 1999, collections began on the Henrys Fork at Ashton, Idaho, to quantify the estimates of chloride leaving the Park on its west boundary, as reported by Norton and Friedman (1985).

Problems in Acquiring Discharge Measurements for the Fall and Madison Rivers

Measurements of the discharges of the Fall and Madison Rivers had to be reconstructed for certain intervals. The following is a description of the methods used to calculate the data.

The flow of the Fall River was measured at the USGS gaging site at Squirrel, Idaho (USGS site 13047500), for the period October 1, 1983, through August 31, 1993. Two irrigation canals (Marysville and Yellowstone) diverted water above the gaging site. The sum of the measured diversions through these two canals was added to the river discharge measured at the Squirrel gage to derive a value of the total flow of the river as it exits the Park.

A major diversion of the Fall River through the Marysville Canal for power generation began operation on September 1, 1993. An alternate gaging station (USGS site 13046995) upstream from the diversions did not begin operation until mid-November 1993 (fig. 2 shows the positions of the Fall

Table 1. Gaging site descriptions.

USGS station no.	Site name and location	Topographic map[b] (km^2)	Drainage[c] area
13047500	Fall River[d] near Squirrel, Idaho, 14.0 km from southwest corner of Yellowstone National Park	Porcupine Lake, Idaho	909
13046995	Fall River above Yellowstone Canal, 9 km from southwest corner of Yellowstone National Park and upstream from all irrigation diversions	Porcupine Lake, Idaho	909
06036905	Firehole River, 4.2 km upstream from Madison Junction	Madison Junction, Wyo.	730
06191000	Gardner River near Mammoth, Yellowstone National Park	Mammoth, Wyo.-Mont.	202
06037000	Gibbon River, 6.4 km upstream from Madison Junction	Madison Junction, Wyo.	306
13046000	Henry's Fork River near Ashton, 0.4 km downstream from power dam	Ashton, Idaho	1,040
06037500	Madison River near West Yellowstone, Mont. (gaging site not shown on 7.5′ quad.; shown on older 15′ quad.	W. Yellowstone, Mont.-Wyo.	1,088
13010200	Snake River at Flagg Ranch, Wyo., 3.7 km south of Snake River Station, at bridge on U.S. Hwy. 287	Flagg Ranch, Wyo.	405
06191500	Yellowstone River at Corwin Springs, Mont.,	Electric Peak, Mont.-Wyo.	6,793

[a] Detailed descriptions of gaging sites are given in the USGS water-data reports for Idaho, Montana, and Wyoming. See Brennan and others (1996), Shields and others (1996), and Smalley and others (1995).

[b] Topographic maps are USGS 7.5-minute quadrangle maps.

[c] Drainage area from USGS water-data reports for Idaho, Montana, and Wyoming. See water-data reports in references.

[d] The Falls River, named by the fur trappers in the early 1800s, was renamed Fall River in 1997.

River gaging sites and diversions). An estimate of the Fall River discharge during the period for which no data were available (September, October, and early November of 1993) was made as follows:

1. The average daily water flow through the power station for September, October, and November of the following year (1994) was calculated by subtracting the sum of the daily discharges measured at Squirrel (USGS site 13047500) and the daily irrigation diversions from the Fall River, from the daily total flow of the river measured at a newly established gaging station upstream from the diversions from the Fall River (USGS site 13046995).

2. The resulting power-station discharge was plotted against the daily average electrical power generated, as recorded at the power station.

3. Power-station discharge for the months for which there was no data was calculated using the relation between power generated and turbine discharge, as calculated in step 2.

4. Power-station discharge was added to the sum of the measured Fall River discharge gaged at the Squirrel site and at the measured diversions for irrigation upstream from that gage.

Although this estimate, calculated on the basis of the sum of four measurements (flow in each of the two irrigation canals, the flow of the river at the Squirrel gage, and the calculated power-plant discharge), is less accurate than a direct measurement of the flow, the added error to the annual discharge is small. This is true because the stage of the river during the period from September through early November was low and constituted only approximately 6 percent of the annual discharge of the Fall River.

The discharge and chloride flux for the Madison River were not measured for WY 1987, 1988, and 1989. However, the Firehole and Gibbon Rivers were gaged for these years above their confluence where they form the Madison River. Because no known streams or hot springs discharge into the Madison River in the Park, we used the sum of the discharges of the Firehole and Gibbon Rivers as a proxy for the discharge of the Madison River.

To determine the amount of subsurface inflow and chloride flux into the Madison River between the confluence of the Firehole and Gibbon Rivers and the Madison River gaging site 24 km downstream, we used data for times when all three rivers were gaged and compared the discharge of the Madison at West Yellowstone with the sum of the discharges of the Firehole and Gibbon Rivers near their confluence. The chloride fluxes were compared in a similar manner.

The first set of calculations, using data for 1984, 1985, and 1986 (Norton and Friedman, 1991), indicated that the discharge of the Madison River measured at West Yellowstone, Wyo., was 11.7 percent greater than the sum of the discharges of the Firehole and Gibbon Rivers. The chloride flux was

3.6 percent greater in the Madison River than the sum of the fluxes of the Firehole and Gibbon Rivers.

Calculations from data reported in this paper, using data for 1990–1994 in addition to data for 1984, 1985, and 1986, resulted in new values for these factors; 6.7 percent added discharge and 5.7 percent added chloride flux in the Madison River compared to the sum of the values of the Firehole and Gibbon Rivers. We used our calculated factors to derive the discharge and chloride flux for the Madison River in 1987, 1988, and 1989, when the discharge of the Madison River was not measured.

Annual Discharge Values

The annual integrated discharge values for the Fall, Firehole, Gibbon, Madison, Snake, and Yellowstone Rivers are given in table 2. In calculating the annual discharge, it is necessary to integrate the instantaneous discharge measurements from the beginning to the end of the water year. For sites where samples had not been collected on October 1 and September 30, we used the published average daily discharges for those days.

In a few cases, the annual discharges as published by the WRD and derived from integration of river-stage measurements made every 15 minutes to calculate annual discharge, showed large disagreement with our data (table 3). For example, the results of our data for the Madison River for WY 1993 are 8 percent greater than those published by the WRD (table 3). Another example is the Gibbon River for WY 1989—we calculated 12.7 percent less discharge than the WRD published value.

By examining our data sets in table 3 (data for 1 water year for one river constitutes a data set), we noted that, in 14 cases out of 91, samples were not collected on the dates prescribed by our collection protocol. To correct the data sets, we added to our data the published average daily discharge values for the dates on which samples were missed. The data added to our original data sets were identified in Friedman and Norton (2000) (no times were listed under the column heading "time" in their report). Both the corrected data sets and the uncorrected data sets (in parentheses) are given in table 3.

Annual Discharge Measurements by Two Different Protocols

In this research we assumed that the river sampling by our protocol where 28 samples (collected at strategic times throughout the water year—weekly at periods of rapid change in discharge and less frequently at times of stable flow rates) would yield accurate measurements of annual river discharge and chloride flux for the river. To test this assumption, we compared the total annual discharge of each river, as calculated by our protocol, and the total annual discharge published by the WRD.

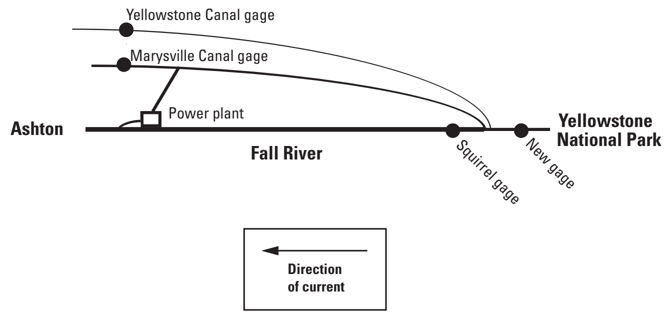

Figure 2. Diagram (not to scale) of the Fall River showing locations of gaging stations and water diversions from the river.

Comparisons of our data with WRD data are given in table 3. The percent differences are given for each river and year. Plots of the discharges calculated by our protocol versus those published by the WRD are shown in figure 3.

For 19 years of record, the average difference in stream flow between the two collection protocols is 0.3 percent with a standard deviation of 4 percent. Because the WRD stage values were collected at 15-minute intervals (35,040 measurements per year), those values are taken to be the true measures of the discharge. The agreement between these two sets of data (fig. 3) indicates that our collection protocol involving only 28 discrete samples is adequate to accurately determine annual discharge of the individual rivers.

Relation Between River Discharge and Chloride Concentration

Plots for each river of the relationship between the chloride concentration and river discharge recorded at the time each sample was taken (fig. 4) show that the relationships are power functions. This indicates that the relation between chloride concentration and river discharge cannot be explained by simple dilution by snow meltwater to the base flow of the river. The base flow is assumed to have a constant input of thermally derived chloride.

We believe that the chloride in the rivers is derived partly from chloride stored in the shallow ground-water system and released by increased ground-water head generated by snowmelt, and partly by a steady flux from deep thermal aquifers that are not affected by changes in the height of the water table. In addition, a small "non-thermal" chloride flux (~7 percent) is attributed to rock weathering, precipitation, and human waste. The contributions from these non-thermal sources can be estimated by examining the chloride concentration of non-thermal streams in the Park, which typically have chloride concentrations of 0.7 to 1 mg/L, in contrast to chloride concentrations of water samples from the streams and rivers that drain thermal features and have chloride concentrations from 2 to 500 mg/L (Norton and Friedman, 1985).

Table 2. Annual discharge from the Fall, Firehole, Gibbon, Madison, Snake, and Yellowstone Rivers.

Water year	Fall River		Firehole River		Gibbon River		Madison River		Snake River		Yellowstone River		Sum of four rivers[a]	
	cfs×10^{10}	m^3×10^8	cfs×10^{10}	m^3×10^8	cfs×10^{10}	m^3×10^8	cfs×10^{10}	m^3×10^8	cfs×10^{10}	m^3×10^8	cfs×10^{10}	m^3×10^8	cfs×10^{10}	m^3×10^8
1983	2.95	8.36					1.73	4.89	3.22	9.11	9.14	25.9	17.1	48.3
1984	3.72	10.52	4.04	1.14	1.17	3.32	1.72	4.86	3.29	9.33	11.4	32.4	20.3	57.5
1985	2.75	7.78	3.43	0.97	1.81	5.01	1.6	4.52	2.47	7.00	8.45	23.9	15.3	43.2
1986	3.17	8.98	4.15	1.17	1.27	3.61	1.95	5.52	3.59	10.2	11.7	33.1	11.8	33.3
1987	1.98	5.60	2.82	0.799	9.46	2.68	1.31[b]	3.71[b]	1.72	4.87	6.77	19.1		
1988	1.84	5.20	2.63	0.744	8.64	2.45	1.16[b]	3.29[b]	1.68	4.76	6.18	17.5	10.9	30.9
1989	2.44	6.92	4.01	1.13	8.82	2.5	1.41[b]	3.99[b]	2.64	7.47	8.80	24.9	15.3	43.4
1990	2.31	6.53	3.61	1.02	9.04	2.56	1.39	3.95	2.62	7.42	9.57	27.1	15.9	45.0
1991	2.43	6..87	4.06	1.15	9.33	2.64	1.47	4.17	2.77	7.83	10.29	29.1	16.9	48.0
1992	1.88	5.32	3.37	0.955	8.23	2.33	1.38	3.92	1.91	5.42	9.04	25.6	14.2	40.3
1993	3.12	8.83	5.16	1.46	9.37	2.65	1.65	4.67	2.86	8.09	11.23	31.8	18.8	53.4
1994	1.96	5.56	3.43	0.972	9.05	2.56	1.52	4.31	1.84	5.21	7.42	21.0	12.7	36.1
1995													18.1[c]	51.2[c]
1996													21.8[c]	61.7[c]
1997	4.31	12.2					2.44	6.92	4.57	12.9	15.91	45.1	27.2	77.1
1998	3.24	9.19					1.94	5.50	3.44	9.73	10.89	30.8	19.6	55.5
1999	3.20	9.05					2.05	5.81	3.61	10.4	12.12	34.3	21.0	59.4
2000	2.71	7.42					1.71	4.84	2.59	7.33	9.14	25.9	16.1	45.7
2001	1.94	5.50					1.42	4.02	1.63	4.50	6.55	18.6	11.5	32.6
2002	2.22	5.14					1.34	3.81	2.50	7.08	8.36	23.7	14.4	39.7
2003	2.41	6.82					1.65	3.83	2.32	6.57	8.70	24.6	15.1	41.8

[a] Sum of the Fall, Madison, Snake, and Yellowstone Rivers.

[b] Calculated value, sum of the discharges of the Firehole and Gibbon Rivers × 1.067. The factor 1.067 is a correction for inflow to the Madison River between the confluence of the Firehole and Gibbon Rivers and the Madison River gaging site at West Yellowstone—see text.

[c] From published USGS WRD data.

Table 3. Comparison, by two different data-collection protocols, of annual discharges of rivers that drain Yellowstone National Park.

[Discharges measured in acre-feet×10^4. Discharges on Fall River from 1983 to 1994 do not include diversions above the gaging station for irrigation. A, data from this report; WRD, data from published values by U.S. Geological Survey Water Resources Division; D, percent difference: ((WRD–A)/WRD)×100. Numbers in parentheses are uncorrected values, as discussed in the text]

Water year	Fall River			Firehole River			Gibbon River			Madison River			Snake River			Yellowstone River		
	A	WRD	D	A	WRD	D	A	WRD	D	A	WRD	D	A	WRD	D	A	WRD	D
1983	68.34	69.53	–2.2	--	--	--	--	--	--	39.67	--	--	73.87	--	--	210.0	219.2	–4.2
1984	85.73	83.05	3.2	26.82	25.79	4.3	9.265	9.494	–2.4	39.43	38.59	2.2	75.62	--	--	262.7	255.2	2.9
1985	60.21	62.06	–3.0	25.17	24.76	1.7	8.147	8.283	–1.6	36.65	37.02	–1.0	56.72	59.64	–4.9	194.0	195.0	–0.5
				(26.11)		(5.5)	(7.867)		(–5.0)				(54.88)		(–8.0)	(187.3)	(–4.2)	
1986	71.10	73.04	–2.6	29.30	28.90	1.4	9.515	9.691	–1.8	44.76	44.57	0.4	82.33	83.32	–1.2	268.1	264.7	–1.3
				(30.43)		(5.3)										(273.1)	(3.3)	
1987	42.69	43.55	–2.0	21.72	21.85	–0.6	6.481	6.477	0.1	31.59	--	--	39.47	40.38	–2.3	155.1	151.5	2.4
																(135.9)	(–10.3)	
1988	39.24	40.68	–3.6	19.84	19.19	3.4	6.035	5.988	0.8	27.86	--	--	38.55	38.18	1.0	142.0	143.3	–0.9
1989	53.10	54.02	–1.7	20.25	21.10	–4.0	9.195	8.771	4.8	30.92	--	--	60.57	62.96	–3.8	202.0	202.8	–0.4
							(7.656)		(–12.7)						(216.3)	(6.7)		
1990	49.83	51.59	–3.2	20.77	20.95	–0.9	8.286	8.152	1.6	31.98	31.99	0.0	60.12	58.54	2.7	219.8	216.6	1.5
																(226.2)	(2.1)	
1991	53.31	51.95	2.6	21.42	21.74	–1.5	9.319	9.365	–0.5	33.78	34.96	–3.4	63.47	63.04	0.7	236.2	231.4	2.1
							(9.000)		(–3.9)									
1992	41.22	42.14	–2.2	18.90	19.33	–2.2	7.744	7.853	–1.4	31.75	31.92	–0.5	43.91	45.09	–2.5	207.6	200.2	3.7
							(6.802)		(–13.4)									
1993	67.68	69.64	–2.8	21.51	21.86	–1.6	11.84	11.49	–3.0	37.82	37.29	–1.4	65.55	65.39	0.2	257.7	251.6	2.4
										(40.29)		(8.0)	(60.40)		(–7.6)			
1994	48.19	--	--	20.76	20.63	0.6	7.88	7.81	0.9	34.96	33.73	3.3	42.23	44.35	–4.8	170.4	174.0	–2.1
1995	--	63.36	--	--	--	--	--	--	--	--	39.95	--	--	71.13	--	--	240.3	--
1996	--	75.45	--	--	--	--	--	--	--	--	48.50	--	--	48.24	--	--	327.7	--
1997	99.0	99.2	–0.2	--	--	--	--	--	--	56.18	57.11	–1.6	104.8	111.4	–5.9	365.2	373.4	–2.2
1998	76.73	74.82	2.6	--	--	--	--	--	--	44.58	44.39	0.04	78.92	77.12	2.3	249.9	255.8	–2.3
1999	73.40	74.45	–1.4							47.20	46.45	1.6	82.97	85.36	–2.8	278.3	281.1	–1.0
2000	62.13	59.94	3.7							39.25	39.86	–1.5	59.42	60.99	–2.5	209.9	511.2	–0.6
2001	44.5	43.33	2.9							32.55	32.18	1.0	37.31	38.33	–2.7	150.4	145.5	3.4
2002	50.91	51.55	–1.2							30.85	30.89	–0.1	57.38	58.68	–2.2	192.0	194.0	–1.0
2003	55.30	56.59	–2.2							31.05	31.51	–1.5	53.22	54.74	–2.8	199.8	202.4	–1.3

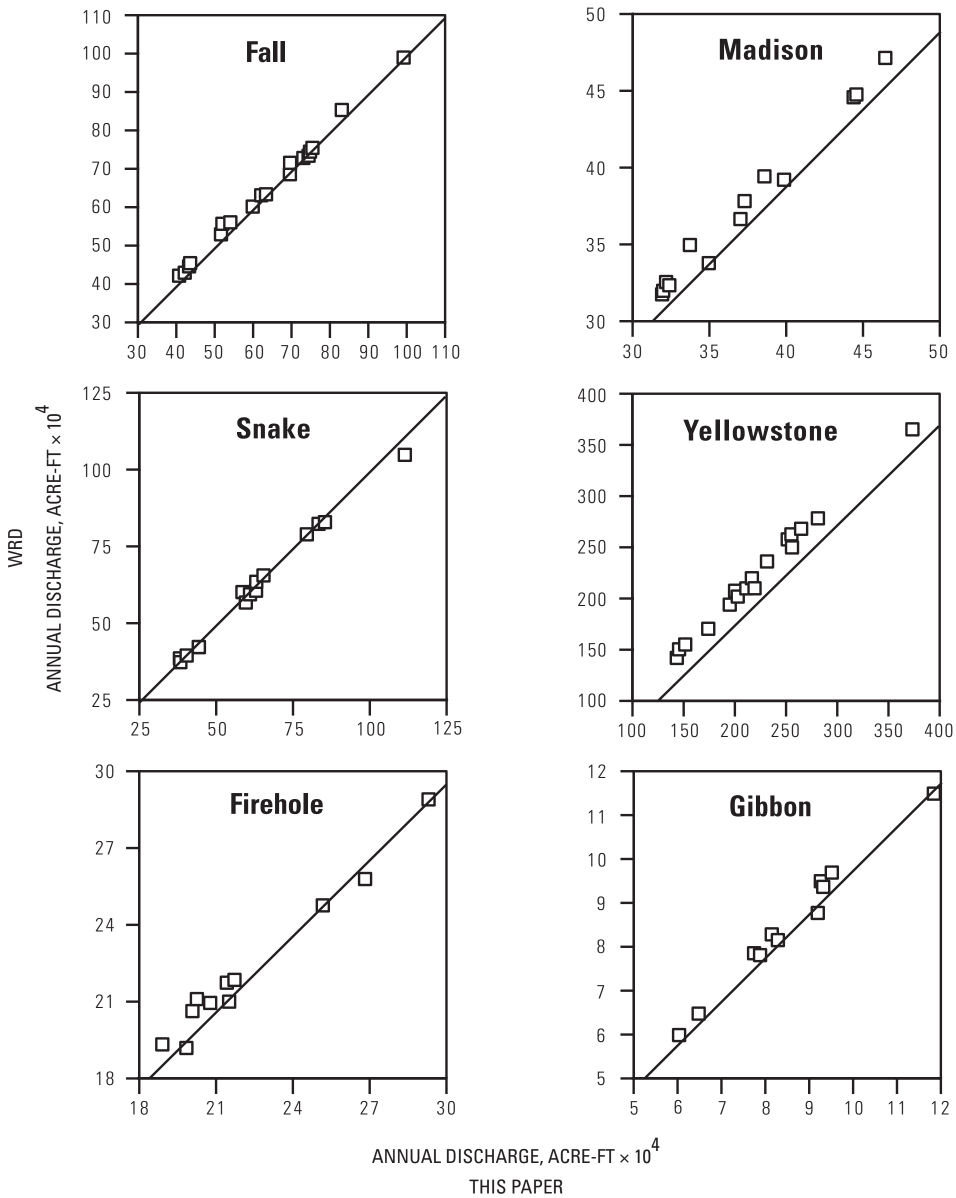

Figure 3. Relationship of annual discharges of six rivers, as calculated in this paper, plotted against discharges published by Water Resources Division of the USGS.

Chloride Flux

Calculation of Chloride Flux

Instantaneous chloride fluxes, tabulated in Friedman and Norton (2000), were calculated by multiplying the chloride concentrations of the samples by the river discharges recorded at the time of sample collection. Annual summations were made by integrating between calculated values for each sample from the beginning of the water year (October 1) to the end of the water year (September 30). If samples had not been collected on October 1 and September 30, the published average daily values of discharge were used, and the chloride concentrations for these discharges were calculated by linear interpolation. Errors introduced by these interpolations are small because at that time of the year the discharges of the rivers were close to minimum flow, and they were changing slowly with time. For other scheduled dates on which no samples were collected, we calculated the chloride concentrations of the water by using the plotted relationships between chloride concentrations and discharges for each river. Those relationships were determined for each river for the measured chloride concentrations of water samples versus the discharge recorded at the time each sample was taken (fig. 4). Integrations were carried out for each water year, and the results are shown in table 4.

The error assigned to the the instantaneous chloride flux calculations is ±5.4 percent. This value is derived from the error of the individual chloride concentration (E=2 percent) and the discharge measurements (E=5 percent) as follows, where E=error.

$$\text{Chloride flux error} = \sqrt{E^2_{\text{chloride}} + E^2_{\text{discharge}}}$$

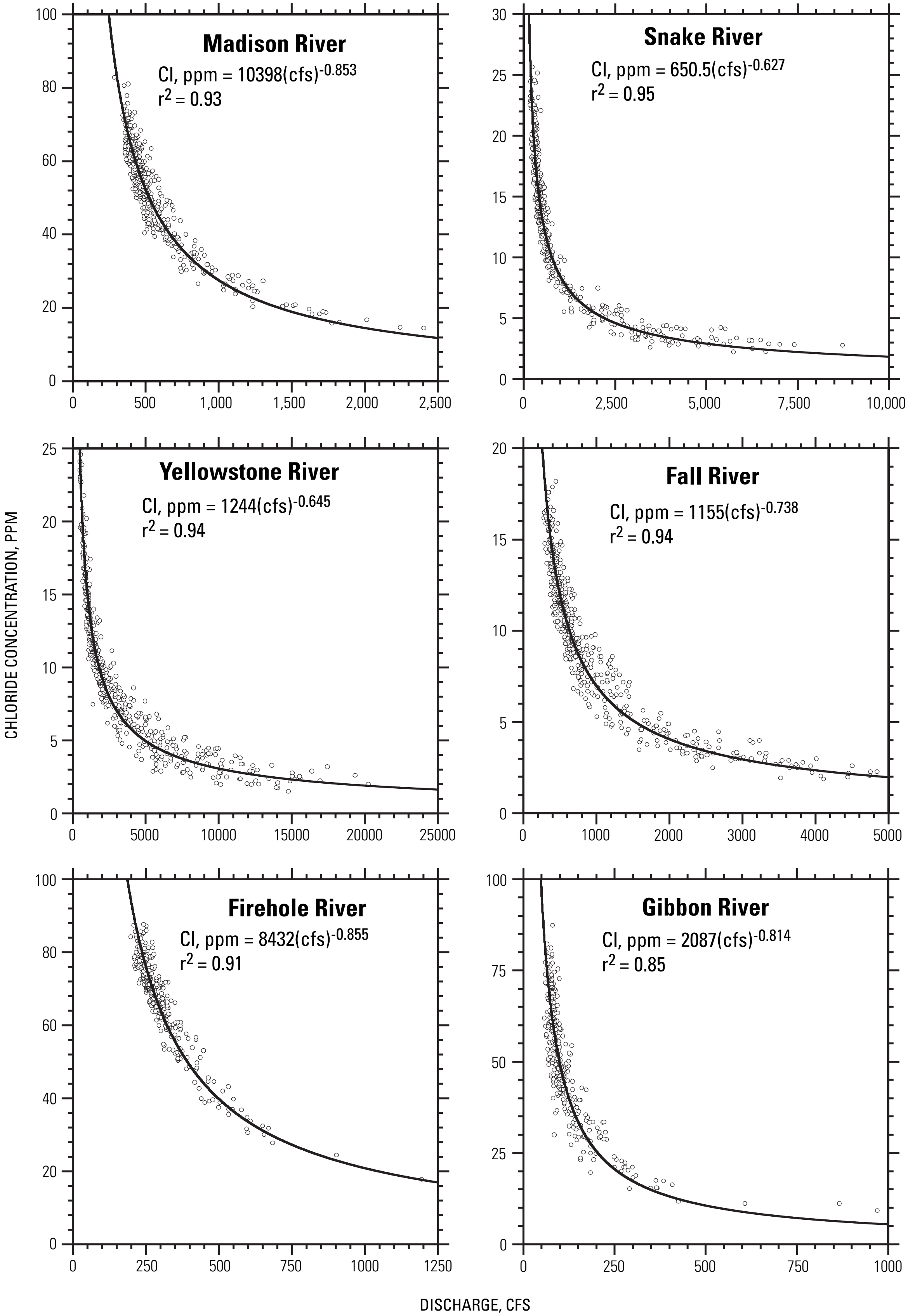

Figure 4. Graphs of chloride concentrations of water samples from six rivers, plotted against discharges measured at the times of collection.

Calculation of Thermal-Chloride Flux

Norton and Friedman (1985) estimated that the background average concentration of non-thermal chloride in the rivers exiting the Park was 0.7 mg/L. This was the sum of chloride contributed by surface-rock weathering, precipitation, and human waste. If this value of non-thermal chloride is subtracted from all of the experimentally determined chloride values, the remaining chloride concentrations represent the thermal chloride derived directly from the hydrothermal system. In this report, the chloride-flux values quoted are thermal chloride unless otherwise stated.

Calculations of the percent of non-thermal chloride for the 19 years of recorded data (table 4) show that it is 7 percent of the total chloride, in comparison to 6 percent reported by Norton and Friedman (1985) on the basis of a much smaller database.

The percentage of thermal chloride compared to total chloride flux differs for each river (table 5). These differences are mainly related to the different proportions of non-thermal chloride versus chloride derived from thermal inflow.

Thermal-Chloride Flux from the Major Rivers

The percent of the total thermal-chloride flux from the Park via each of the major rivers (not including the flux from the west boundary of the Park) for the 19 years of measurement is given in table 5. These values do not differ significantly from those reported earlier by Norton and Friedman (1985).

Thermal-Chloride Flux from the West Boundary of the Park

In their paper on chloride flux from Yellowstone National Park, Norton and Friedman (1985) calculated the chloride flux from the west boundary of the Park as 5 percent of the total leaving the Park. That value was derived from published data (Whitehead, 1978) on stream flow and chloride concentration from several streams that flow from the west boundary into the Henrys Fork River. The data derived from several samples of each stream, collected at infrequent intervals over a period of several years. In 1998, we established a collection site on the Henrys Fork River near Ashton, Idaho (fig. 1), to quantify this important source of chloride. This site is southwest of the Park, and it should record all of the thermal chloride that leaves the Park along the west boundary. For water year 1999, the total chloride flux was 5.5×10^9 g, of which 4.1×10^9 g was thermal chloride. This thermal chloride was 7.6 percent of the total thermal chloride (53.3×10^9 g) that exited the Park during that water year. The total annual chloride flux exiting the Park via the four major rivers, as well as the total that includes that exiting via the Henrys Fork River, are shown in table 6.

Seasonal Variation of Chloride Flux

Because 93 percent of the chloride exiting the Park is hydrothermally derived chloride, we would not expect this flux to show short time (seasonal) variations. However, Fournier and others (1976), Norton and Friedman (1985), and the present authors noted seasonal changes in flux, with a maximum that coincided with the peak of snowmelt runoff (fig. 5). Fournier and others (1976) and Ingebritsen and others (2001) ascribed these seasonal variations in chloride flux to entrapment of thermal chloride in the soil during winter months, associated with freezing, and subsequent release of the trapped chloride during snowmelt. However, the deep snow cover over most of Yellowstone National Park during the winter insulates the ground and prevents the soil from freezing, making this explanation improbable. In addition, the ground in the major thermal areas remains unfrozen and free of snow in the winter. Don White (oral commun., 1984) postulated that the seasonal variations of chloride were caused by entrapment of chloride in the soil during summer and fall, associated with increased temperatures and reduced water-table levels. Although some storage of chloride in the soil probably occurs, it is difficult to associate the synchronism between river discharge and chloride flux to this process. The present authors offer another explanation.

Friedman and Norton (1990) and Friedman and others (1993) reported that samples from individual thermal springs, collected close to their orifices, showed seasonal changes in discharge similar to those of the major rivers. Although the hot-spring discharges increased during snowmelt and decreased in the fall and winter, the chloride concentrations changed very little. They suggested that the major cause of this seasonality in hot-spring discharge was changes in the height of the local water table. Increased water-table height during snowmelt increased hydrostatic pressure above the aquifers that fed the springs and enhanced their flow. Because the hot-spring aquifers and the local water-table water did not mix—at least not in the short time represented by our collections—the chloride concentrations in the hot-spring effluent did not change, and they were independent of discharge rates. As a result, the increased hot-spring discharges during times of high water table associated with snowmelt runoff caused increases in chloride flux during those periods. Because chloride in the rivers is derived mainly from thermal springs, this increase in chloride derived from hot springs explains the observed seasonal increase in chloride flux in the rivers.

It is important to note that the seasonal increases in discharge and chloride flux for the Madison, Firehole, and Gibbon Rivers are not as large as those for the Fall, Snake, and Yellowstone Rivers (fig. 5). This may be explained by the fact that the former rivers drain the major geyser-containing areas of the Park—Upper, Midway, and Lower Geyser Basins, as well as Norris Geyser Basin. We believe that the geyser basins receive a greater proportion of thermal water of deep origin that is isolated from the effects of the local water table than do the thermal features that drain into the Fall, Snake, and Yellowstone Rivers. Another contributing factor that tends to lower the seasonal variation in discharge and chloride flux in the Madison, Firehole, and Gibbon Rivers is the presence of large areas of thermally heated ground in the drainage areas of these rivers. During the winter, snow melting on these heated areas reduces the amount of snow remaining to contribute to early summer runoff.

Table 4. Annual chloride flux, both total and thermal, from the Fall, Madison, Snake, and Yellowstone Rivers.

[All values reported in grams × 10^9]

Water year	Fall River		Madison River		Snake River		Yellowstone River		Sum of four rivers	
	Total	Thermal	Total	Thermal	Total	Thermal	Total	Thermal	Total	Thermal
1983	6.18	5.59	24.85	24.51	7.23	6.60	19.57	17.10	57.83	53.79
1984	6.34	5.60	23.64	23.30	7.17	6.51	20.19	17.92	57.34	53.34
1985	6.24	5.70	23.59	23.28	7.25	6.05	17.49	15.64	54.57	50.67
1986	6.35	5.71	24.95	24.57	8.13	7.42	21.66	19.20	61.09	56.89
1987	5.67	5.28	21.77	21.71	5.80	5.21	16.58	15.18	49.82	47.37
1988	5.11	4.75	21.62	21.60	5.26	4.93	14.38	13.13	46.37	44.40
1989	5.55	5.06	23.18	23.12	6.42	5.90	17.24	15.49	52.39	49.58
1990	6.23	5.77	24.68	24.40	7.33	6.81	18.81	16.90	57.05	53.89
1991	6.16	5.68	23.91	23.62	7.21	6.66	18.93	16.66	56.22	52.62
1992	5.57	5.20	23.51	23.24	6.03	5.65	15.88	14.09	50.99	48.17
1993	6.12	5.42	23.91	22.90	7.41	6.54	17.48	15.11	54.32	49.97
1994	5.59	5.16	23.49	23.19	5.58	5.21	15.33	13.86	49.99	47.42
1995										
1996										
1997	6.86	6.00	24.35	23.86	8.05	7.15	20.73	17.58	59.99	54.59
1998	5.17	4.55	22.16	21.31	6.98	6.18	18.08	15.92	52.39	47.96
1999	5.19	4.53	23.46	23.05	6.58	5.86	18.19	15.79	53.42	49.23
2000	5.74	5.22	22.77	22.15	6.46	5.95	16.02	14.20	50.99	47.51
2001	5.66	5.18	22.31	22.03	5.75	5.43	16.09	14.84	49.81	47.48
2002	5.37	4.80	22.62	22.35	7.59	7.05	15.09	13.46	50.67	48.02
2003	5.31	4.83	21.71	21.45	5.86	5.40	15.55	13.82	48.43	45.50

Modeling of Thermal and Non-Thermal Inputs to the Major Rivers

The following is an attempt to model the various inputs to the major rivers to explain the chloride versus discharge data (fig. 4) and the seasonal changes in chloride concentrations that are observed (fig. 5).

Gardner River

In modeling inputs to the Gardner River, we have used the base flow of the river as measured at the gaging station located at the confluence of the Gardner with the Yellowstone River as one input, with an inflow of 70 cfs and a chloride concentration of 0.7 ppm. This is the non-thermal chloride concentration reported by Norton and Friedman (1985) for streams within the Park that do not contain thermal water and includes chloride input from rock weathering. Another input to the river is snow meltwater, which varies in quantity from zero to a maximum of 800 cfs and has a chloride concentration of 0.2 ppm, as reported by Norton and Friedman (1985). The final input is thermal chloride from Mammoth Hot Springs, with a measured chloride of 170 ppm and a seasonally varying flow of 22 cfs at base-flow conditions to 27 cfs at maximum river flow. The amount of this hot-spring water that enters the river at base flow was calculated from the amount necessary to satisfy the chloride concentration of the river at base flow (41 ppm). The amount that discharges into the river at snowmelt maximum is also calculated to satisfy the measured chloride concentration of the Gardner River at maximum discharge (~6 ppm). Table 7 shows the details of these calculations of discharge and chloride concentrations at various river flows. The calculated chloride concentration versus discharges from table 7 are plotted as large filled circles on a plot of measured chloride concentration versus discharge in figure 6. The calculated data from table 7 fits precisely with the least-mean-squares average for the measured data.

To observe the result of assuming that the thermal water input does not vary seasonally as assumed in table 7, we have plotted data presuming that the thermal water from Mammoth Hot Springs is constant at 22 cfs, the postulated input

Table 5. Percent thermal chloride as compared to total chloride for each river, and percent thermal chloride compared to total thermal chloride exiting in the Park.

River	Percent thermal chloride compared to total chloride for each river	Percent thermal chloride for each river compared to total chloride exiting the Park
Fall	91.5	10
Madison	98.6	46
Snake	91.4	12
Yellowstone	88.7	32

Table 6. Total thermal-chloride flux from Yellowstone National Park, Wyoming, water years 1983–2003.

Water year	Four rivers[a] thermal-chloride flux $g \times 10^{10}$	Four rivers plus Henrys Fork River thermal-chloride flux[b] $g \times 10^{10}$
1983	5.38	5.76
1984	5.33	5.70
1985	5.07	5.42
1986	5.69	6.08
1987	4.74	5.07
1988	4.44	4.75
1989	4.96	5.31
1990	5.39	5.77
1991	5.26	5.63
1992	4.82	5.16
1993	5.00	5.35
1994	4.72	5.05
1995		
1996		
1997	5.46	5.84
1998	4.80	5.14
1999	4.92	5.26
2000	4.74	5.07
2001	4.75	5.08
2002	4.80	5.14
2003	4.55	4.87

[a] The totals are the sums of the values for the Fall, Madison, Snake, and Yellowstone Rivers.
[b] Total flux is calculated by summing the flux from the four rivers and multiplying by 1.07. The factor 1.07 corrects the total thermal flux for thermal-chloride flux discharged via the Henrys Fork River.

to the Gardner River at base flow. The results of this calculation are shown as squares enclosing a cross in figure 6, and these points deviate from the least-mean-squares average for the measured data points. This comparison lends credence to the assumption that the inflow of thermal water varies seasonally, increasing by 23 percent at high river discharge.

Fall River

A calculation for inflow to the Fall River similar to that made for the Gardner is given in table 8. In this calculation, the thermal-water chloride concentration (85 ppm) is that reported by Friedman and others (1993) for springs in the southwestern part of the Park that enter the Fall River. The input of thermal water varies seasonally from 70 to 115 cfs, a 62 percent increase during the time of maximum snowmelt input. The data derived from the model plots (large filled circles in fig. 7) almost exactly on the least-mean-squares average to the measured data as plotted on figure 4. As before, we have plotted the data assuming that the amount of thermal water input is constant, and again these data deviate from the least-mean-squares line.

Madison River

For the Madison River, we used a value of 400 ppm for the thermal water input. This is based on published values for the analysis of many of the geysers and hot springs in the Upper, Midway, Lower, and Norris Geyser Basins reported by Thompson and others (1975). A 31-percent seasonal increase in thermal chloride is assumed. Again, the data calculated from the model (table 9 and fig. 8) fits the least-mean-squares average for the measured chloride concentration versus discharge (fig. 4), whereas the data calculated assuming a constant thermal-chloride water input does not fit the measured data.

Snake River

Thermal input to the Snake River was assumed to have a chloride concentration of 300 ppm and to increase from 14 cfs at base flow to 55 ppm at maximum flow of the river, a seasonal change of 293 percent (table 10 and fig. 9). Again, the model data fits the measured least-mean-squares average (fig. 4), whereas the data using a seasonally unvarying input does not fit the average.

Yellowstone River

For the Yellowstone River we used two sources of thermal water—thermal water input from Mammoth Hot Springs, for which we used the data in table 7, and other thermal water introduced upstream from the confluence of the Gardner River. This second source was assumed to have a chloride concentration of 30 ppm and to vary seasonally from 500 to 950 cfs. The results of these calculations are given in table 11 and plotted in figure 10. Again, results from the seasonally varying input of thermal water fit the measured data, but the data calculated assuming a fixed amount of thermal water input does not agree with the measured data.

Origin of the Seasonal Increase of Chloride in the Major Rivers of Yellowstone National Park

From the measured values of chloride flux in the rivers of the Park, it is obvious that the flux increases during snowmelt. In the above modeling of water inflow to the individual rivers, we have shown that this increase in chloride flux is mainly due to seasonal changes in thermal chloride input. However, it is not proven that all of this thermal chloride input is caused by an increased flow of hot springs. It is possible that these seasonal changes in chloride flux result from changes in the concentration of chloride in snowmelt runoff due to solution of chloride stored in the soil during summer. This latter process

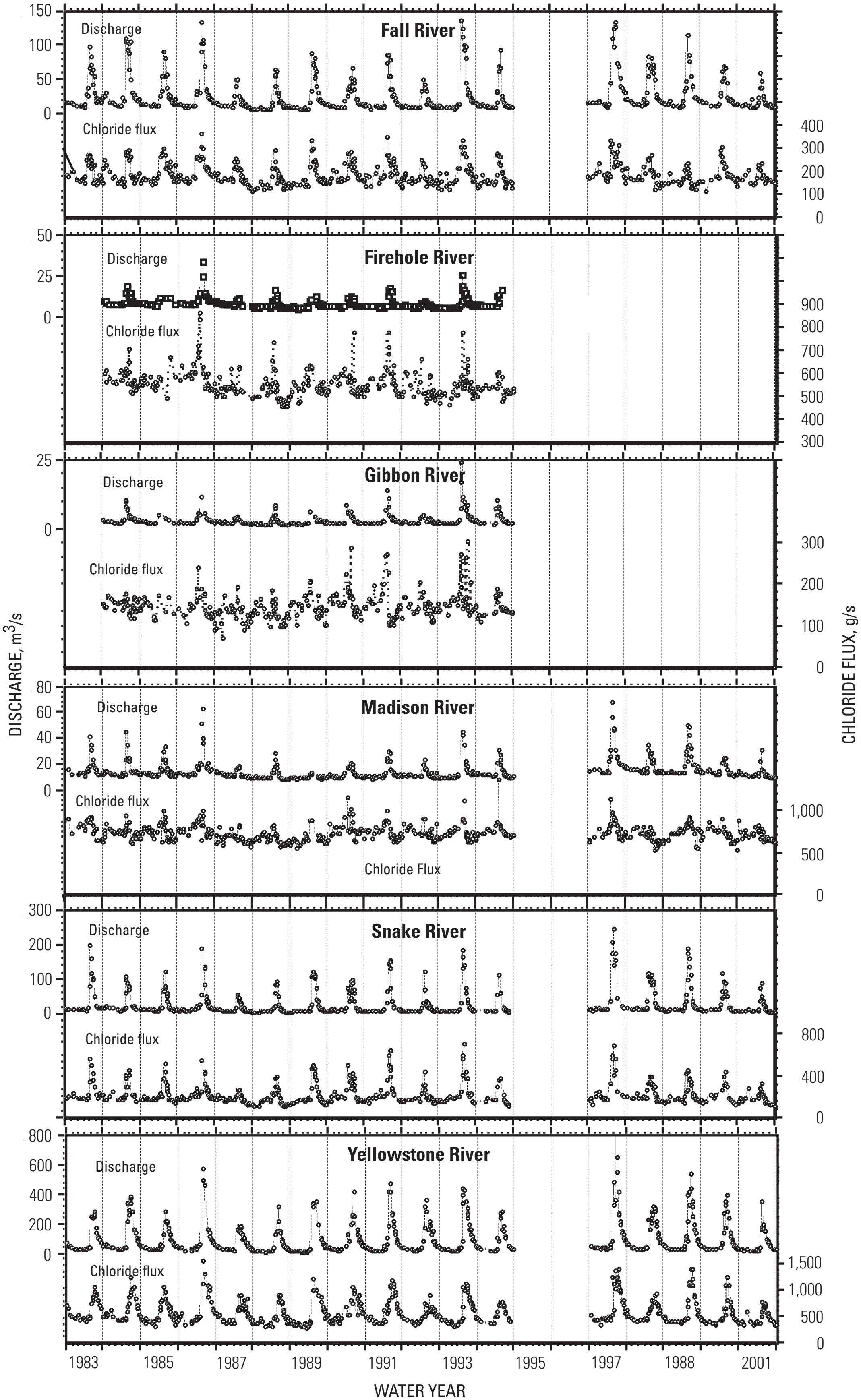

Figure 5. Graph showing instantaneous values for discharge and chloride flux for the Fall, Firehole, Gibbon, Madison, Snake, and Yellowstone Rivers for water years 1983 through 1994 and 1997 through 2001.

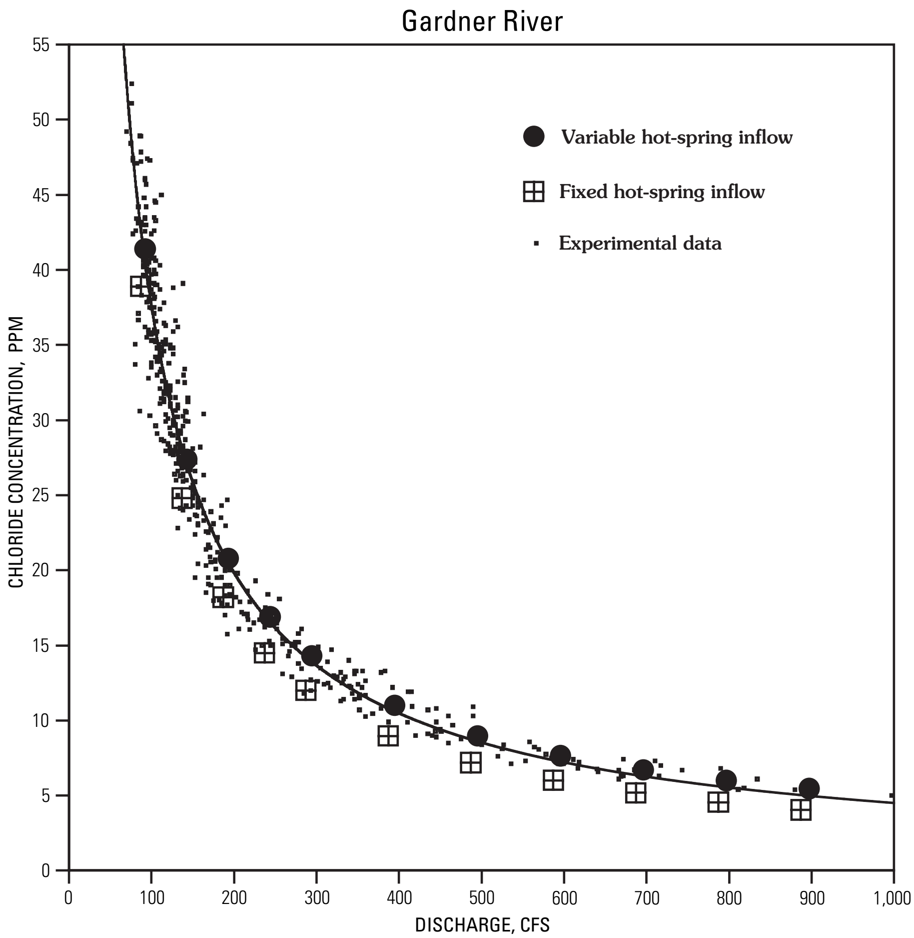

Figure 6. Graph of chloride concentration versus discharge for the Gardner River showing experimental data and models of inflow to the river from various sources.

may be a factor in explaining the seasonality of chloride flux in the rivers. However, we have observed that some springs have a constant chloride concentration that does not change when the discharge of the spring increases during snowmelt. For example, the discharge of Norris Geyser Basin measured at Tantalus Creek can vary by a factor of three, but the chloride concentration of the discharge remains constant at 450±50 ppm. In addition, thermal streams in the Boundary Creek area of the Park display a similar pattern of behavior, where the discharges of these streams increases many fold during snowmelt, but their chloride concentration remains constant throughout the year. Based on these observations, we favor the explanation for the anomalous chloride flux during snowmelt to increased flow of hot springs that discharge into the rivers.

Long-Term Variations in Chloride Flux

In addition to seasonal changes in flux that we attribute to the height of the shallow ground-water table, there are longer term changes, as illustrated in figure 11, showing a plot of the annual thermal-chloride flux from the Madison, Yellowstone, Snake, and Fall Rivers for the 19 years of measurement (21 years of record). These longer term changes also are reflected in the sum of the annual chloride fluxes from the four rivers. The 21-year record of total thermal chloride exiting the Park via the four major rivers shows a decline of about 0.4 percent/year (fig. 12). This change does not appear to be significant due to the scatter in the data that is indicated by the low coefficient of determination (r^2=0.26). In the next section we show that correcting these annual thermal-chloride values for climatic factors that affect the flux results in significant changes in the corrected chloride flux during the 21-year interval.

Effect of Climate on Chloride Flux

The annual chloride fluxes in the rivers are related to the discharges of the rivers, which in turn are related to variations of annual precipitation on their drainage areas (fig. 12). Thus, annual variations in climate affect the chloride flux exiting the Park.

Because of the relationship between thermal-chloride flux and river discharge, which we document, we corrected the thermal-chloride flux for variations in river discharge. To adjust the thermal-chloride flux for river discharge, we normalized the annual chloride-flux data to a common river discharge, which was the average discharge for the 19 years of measurement. This was done by adding to each value of the annual thermal-chloride flux a factor 2.5 times the difference between the river-discharge value for that year and the average discharge. This correction increased the r^2 value of the linear least-mean-squares regression fit to the data from 0.26 to 0.57.

The factor 2.5 that was used to make these adjustments was determined by trial and error to obtain the largest regression coefficient for the linear least-mean-squares regression. It is important to note that the slope of the regression line shows a significant decrease of 0.5 percent per year in chloride flux, in contrast to the unadjusted flux decrease of 0.4 percent per year, which we previously did not consider significant due to the scatter in the uncorrected data. During the time in which the chloride flux showed a decrease (1983–2001), both precipitation and river discharge decreased (from 1983 to 1990), and then increased from 1991 to 2003 (fig. 13). The adjusted results, together with the unadjusted annual chloride flux, are plotted in figure 13.

Inasmuch as variations in precipitation and river discharge are correlated (figs. 14 and 15), it should be possible to use precipitation to correct the thermal-chloride flux for the effect of climate. There are only five precipitation collection sites in Yellowstone National Park. However, the correlation (r^2=0.83) between the sum of the precipitation measurements at the five sites and the total discharge of the four rivers draining the park (fig. 15) indicates that the sum of the data from the five precipitation-collection sites, which are distributed throughout the Park, is a good approximation of the precipitation over the Park, and therefore it can be used to correct the annual thermal-chloride flux for the influence of climate on chloride flux.

To determine whether correction of the annual thermal-chloride flux for annual changes in precipitation will result in a data set with less scatter than the data set that was corrected for annual changes in river discharge, we normalized the unadjusted annual thermal-chloride values to a common precipitation value, which is the average precipitation for the years in which we measured chloride flux. This was done by adding 5 times the difference between the annual-precipitation values and the average precipitation from the annual thermal-chloride flux values. The factor 5 was determined by trial and error to obtain the largest regression coefficient for the linear least-mean-squares regression. This resulted in a data set with an r^2=0.37 and an annual decline of 0.7 percent. We conclude that correcting the annual thermal-flux values for changes in annual river discharge yields a data set with slightly less scatter than a data set corrected for changes in annual precipitation.

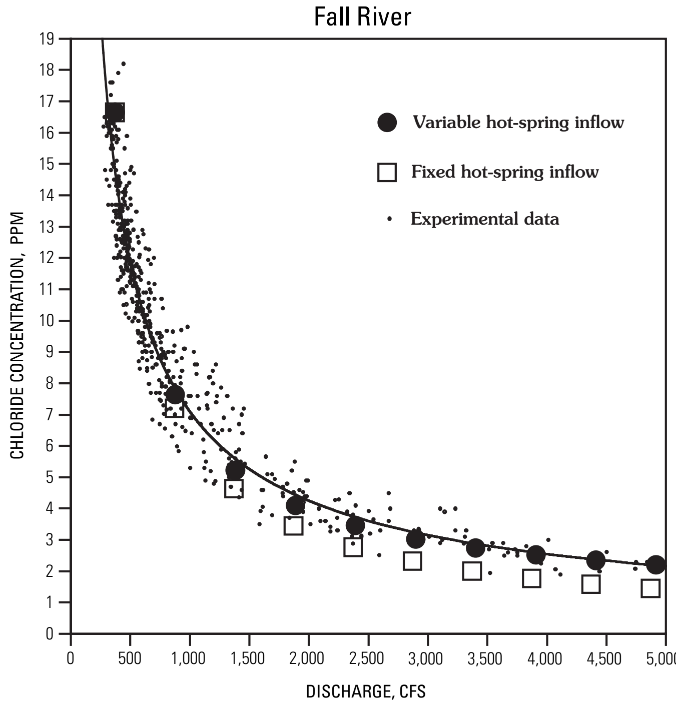

Figure 7. Graph of chloride concentration versus discharge for the Fall River showing experimental data and models of inflow to the river from various sources.

Table 7. Model data for the Gardner River.

River input		Runoff		Hot spring		Total	
cfs	Cl (ppm)	cfs	Cl (ppm)	cfs	Cl (ppm)	cfs[a]	Cl (ppm)[b]
70	0.7	0		22	170	92	41.2
70	0.7	50	0.2	22.5	170	142.5	27.3
70	0.7	100	0.2	23	170	193	20.6
70	0.7	150	0.2	23.5	170	243.5	16.7
70	0.7	200	0.2	24	170	294	14.2
70	0.7	300	0.2	24.5	170	394.5	10.8
70	0.7	400	0.2	25	170	495	8.8
70	0.7	500	0.2	25.5	170	595.5	7.5
70	0.7	600	0.2	26	170	696	6.6
70	0.7	700	0.2	26.5	170	796.5	5.9
70	0.7	800	0.2	27	170	897	5.4

[a] Total cfs equals the sum of the flows of River input, Runoff, and Hot spring.
[b] Chloride concentration in "Total cfs" calculated as follows:
[(column 1)(column 2)+(column 3)(column 4)+(column 5)(column 6)]/column 7.

The long-term changes in chloride flux that we observed contradict the statement made by Ingebritsen and others (2001) who considered the limited data available to them and stated "***the Cl-flux data set shows little evidence of decadal-scale trends in hydrothermal discharge." This contradiction underscores the necessity of securing long-term data sets.

Long-Term Changes in Thermal-Water Outflow from Mammoth Hot Springs

A recent decline in the thermal-water output of a major thermal feature in Yellowstone was noted by Sorey and Colvard (1997). They documented a decline of 15 percent in the output of thermal water from Mammoth Hot Springs from 1987 to 1994 (1.8 percent per year). Their approach involved direct measurement of the flow of Hot River (also known as Boiling River), the major surface discharge from the area, with adjustments to the data to correct for Gardner River inflow into Hot River above its gaging site via a sinkhole in the Gardner River. Beginning in 1985, we used a different method to monitor the thermal-chloride flux discharge of Mammoth Hot Springs. We measured the chloride flux in the Gardner River downstream from the point where both surface and subsurface discharges of the Mammoth Hot Springs enter the river. Measurements of chloride flux in the Gardner River above and below Mammoth Hot Springs show that 90 percent of the chloride in the Gardner River below Mammoth Hot Springs is contributed by the hot springs. We used the chloride flux as measured in the Gardner River at its gaging station below Mammoth Hot Springs to monitor the discharge of chloride from the Mammoth Hot Springs system. To correct these measurements for chloride in the river water before it reaches Mammoth Hot Springs, we multiplied the chloride concentration by 0.9. This coefficient was determined by comparing the chloride concentration of samples collected at high and low river stages at a site below the "High Bridge" (several miles above Mammoth Hot Springs) to the chloride values determined from samples collected below the hot springs. These values then were used to calculate thermal-chloride flux. Our data for 1987–1994, the same period as that used by Sorey and Colvard, shows a decline of 20 percent, as compared to the 15 percent found by them. However, the data from 1995 to 2003, if fitted by a linear least-mean-squares solution—the solid line in figure 16—shows a decline of 1 percent during the past 19 years. Note that the relatively constant thermal chloride flux for the Mammoth Hot Springs system is in contrast with the decline in thermal chloride flux for the entire Yellowstone hydrothermal system.

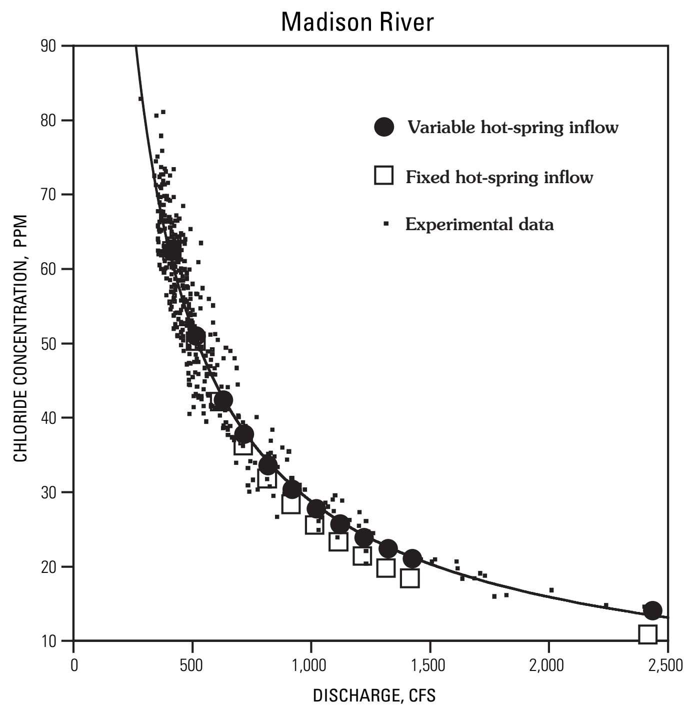

Figure 8. Graph of chloride concentration versus discharge for the Madison River showing experimental data and models of inflow to the river from various sources.

Table 8. Model data for the Fall River.

River input		Runoff		Hot spring		Total	
cfs	Cl (ppm)	cfs	Cl (ppm)	cfs	Cl (ppm)	cfs[a]	Cl (ppm)[b]
300	0.7	0		70	85	370	16.7
300	0.7	500	0.2	75	85	875	7.64
300	0.7	1,000	0.2	80	85	1,380	5.22
300	0.7	1,500	0.2	85	85	1,885	4.10
300	0.7	2,000	0.2	90	85	2,390	3.46
300	0.7	2,500	0.2	95	85	28,955	3.03
300	0.7	3,000	0.2	100	85	3,400	2.74
300	0.7	3,500	0.2	105	85	3,905	2.52
300	0.7	4,000	0.2	110	85	4,410	2.35
300	0.7	4,500	0.2	115	85	4,915	2.21

[a] Total cfs equals the sum of the flows of River input, Runoff, and Hot spring.
[b] Chloride concentration in "Total cfs" calculated as follows:
[(column 1)(column 2)+(column 3)(column 4)+(column 5)(column 6)]/column 7.

Is Yellowstone Losing Its Steam?

The rapid decline in output of thermal-chloride flux from the Yellowstone National Park hydrothermal system documented by this study, added to the decrease in the frequency of eruptions of Old Faithful Geyser (fig.17), give cause for concern. However, if the decrease in activity of the Yellowstone hydrothermal system is a response to deflation of the caldera, as measured by depression of the area under Yellowstone Lake that occurred from 1985 through 1995, then the decrease possibly will be reversed in response to future tectonic changes in Yellowstone National Park. The area occupied by Yellowstone Lake increased in elevation about 2 cm/yr from about 1923 to 1984 (Dzurisin and others, 1994). It was stable from 1984 through 1985; it decreased in elevation by 2 cm/yr from 1985 through 1995 and has begun to inflate again (Wicks and others, 1998). The inflation of the caldera was explained by Dzurisin and others (1994) as follows. The deep hydrothermal system was pressurized by fluids released from a crystallizing body of rhyolitic magma beneath the caldera. It then was trapped beneath a self-sealing layer near the base of the hydrothermal system. Subsequently, there was aseismic intrusion of magma into the lower part of the sub-caldera magma body. They attributed the subsidence that followed inflation of the caldera to depressurization and fluid loss from the deep hydrothermal system and sagging of the caldera floor in response to regional crustal extension. Our evidence suggests that, during inflation, increased fluid pressure at depth results in increased loss of vapor to the shallow hydrothermal system and that, during deflation, lower fluid pressure results in less vapor released from the magma to interact with the shallow geothermal system.

It is possible that the caldera will continue to inflate and deflate over 10- to 20-year intervals and that the hydrothermal system will fluctuate in synchronism with the inflation-deflation. The lack of previous monitoring data related to the Yellowstone hydrothermal system makes it difficult to predict future changes, and it underscores the necessity for future monitoring.

In addition to climatic factors, flux changes might be due to cooling and crystallization of the magma or to changes in the magma-effusion rate beneath the Park (Fournier, 1989). The first process is slow, and it should not result in any observed changes in chloride flux over periods of 50–100 years. The second process is episodic and can result in rapid changes in heat and chloride fluxes.

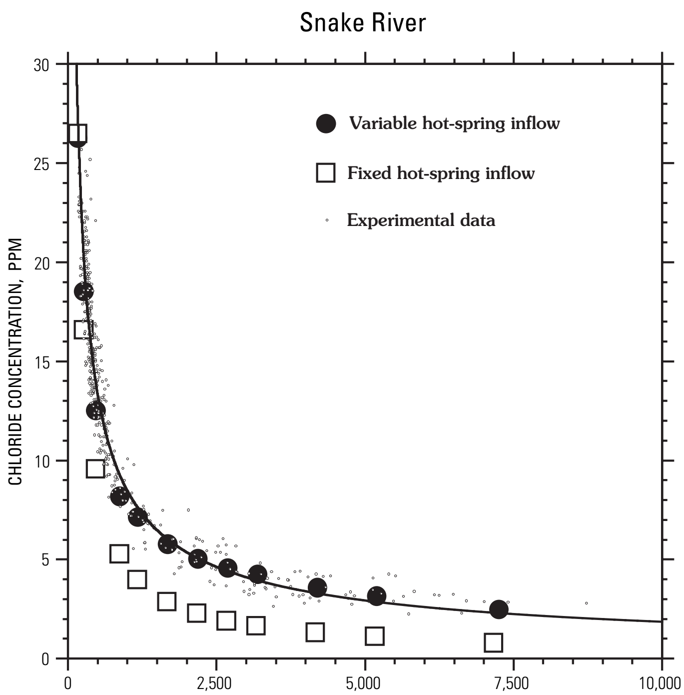

Figure 9. Graph of chloride concentration versus discharge for the Snake River showing experimental data and models of inflow to the river from various sources.

Table 9. Model data for the Madison River.

River input cfs	River input Cl (ppm)	Runoff cfs	Runoff Cl (ppm)	Hot spring cfs	Hot spring Cl (ppm)	Total cfs[a]	Total Cl (ppm)[b]
350	0.7	0		64	400	414	62.4
350	0.7	100	0.2	65	400	515	51.0
350	0.7	200	0.2	66	400	630	42.4
350	0.7	300	0.2	67	400	717	37.8
350	0.7	400	0.2	68	400	818	33.6
350	0.7	500	0.2	69	400	919	30.4
350	0.7	600	0.2	70	400	1,020	27.8
350	0.7	700	0.2	71	400	1,121	25.7
350	0.7	800	0.2	72	400	1,222	23.9
350	0.7	900	0.2	73	400	1,323	22.4
350	0.7	1,000	0.2	74	400	1,424	21.1
350	0.7	2,000	0.2	84	400	2,434	14.1

[a] Total cfs equals the sum of the flows of River input, Runoff, and Hot spring.
[b] Chloride concentration in “Total cfs” calculated as follows:
[(column 1)(column 2)+(column 3)(column 4)+(column 5)(column 6)]/column 7.

Heat Flow from the Yellowstone Hydrothermal System

Fournier and others (1976) estimated that about 41,500 metric tons of chloride and more than 100 million metric tons of water are discharged annually by Yellowstone hot springs. Using the chloride inventory method of Ellis and Wilson (1955), Fournier and others estimated the convective heat flow from the Park to be 4.02×10^{16} cal/yr. Our data, covering a 21-year interval, yields an average thermal-chloride flux of 50,200 metric tons of chloride. Use of the Ellis and Wilson method and the assumptions of Fournier and others (1976) result in a calculated convective heat flow of 4.86×10^{16} cal/yr, a value about 20 percent greater than the estimate of Fournier and others (1976).

Summary and Conclusions

1. Using our collection protocol of 28 samples per year and collecting samples frequently during the spring runoff peak and less frequently during periods of reduced flow, we calculated annual discharges of the rivers draining Yellowstone National Park that agree within 0.3 percent with the values of discharges calculated by the WRD using instrumented stage measurements recorded every 15 minutes (35,040 measurements/yr).
2. Normalization of the laboratory determinations of chloride concentrations to gravimetrically prepared chloride standards yields chloride determinations that are accurate to 1–3 percent (average 2 percent) of the amount present.
3. The accuracy of the calculated annual chloride flux (±5.4 percent) resulted from the combination of our sampling and analytical protocols.
4. One year of measurement of the chloride flux exiting the west boundary of the Park via the Henrys Fork River indicates that 7.6 percent of the total thermal chloride exiting the Park left along the west boundary.

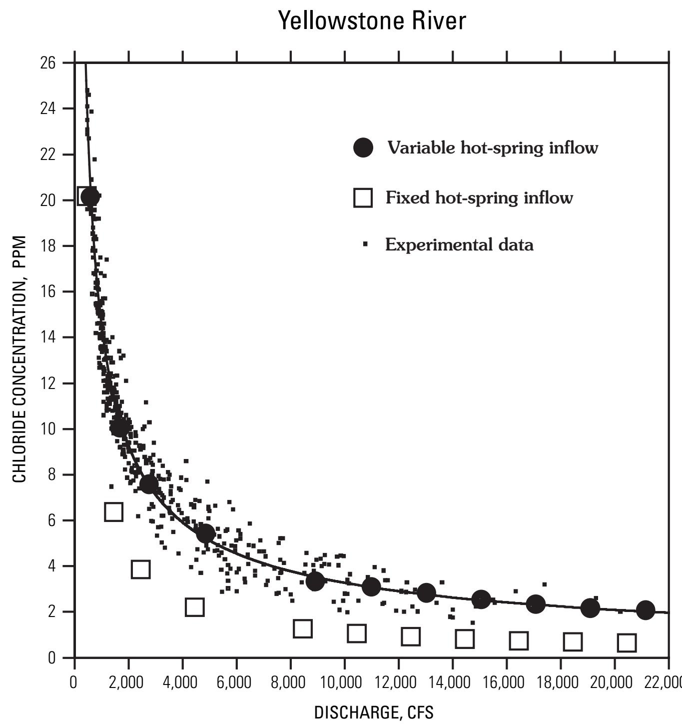

Figure 10. Graph of chloride concentration versus discharge for the Yellowstone River showing experimental data and models of inflow to the river from various sources.

Table 10. Model data for the Snake River.

River input		Runoff		Hot spring		Total	
cfs	Cl (ppm)	cfs	Cl (ppm)	cfs	Cl (ppm)	cfs[a]	Cl (ppm)[b]
150	0.7	0		14	300	164	26.3
150	0.7	100	0.2	16	300	266	18.5
150	0.7	300	0.2	19	300	469	12.5
150	0.7	700	0.2	23	300	872	8.19
150	0.7	1,000	0.2	27	300	1,175	7.15
150	0.7	1,500	0.2	31	300	1,678	5.78
150	0.7	2,000	0.2	35	300	2,182	5.04
150	0.7	2,500	0.2	39	300	2,686	4.58
150	0.7	3,000	0.2	43	300	3,190	4.26
150	0.7	4,000	0.2	47	300	4,194	3.58
150	0.7	5,000	0.2	51	300	5,196	3.16
150	0.7	7,000	0.2	55	300	7,250	2.48

[a] Total cfs equals the sum of the flows of River input, Runoff, and Hot spring.
[b] Chloride concentration in "Total cfs" calculated as follows:
[(column 1)(column 2)+(column 3)(column 4)+(column 5)(column 6)]/column 7.

Figure 11. Graph of the annual thermal-chloride flux for the Fall, Madison, Snake, and Yellowstone Rivers for the water years 1983–1994 and 1997–2001.

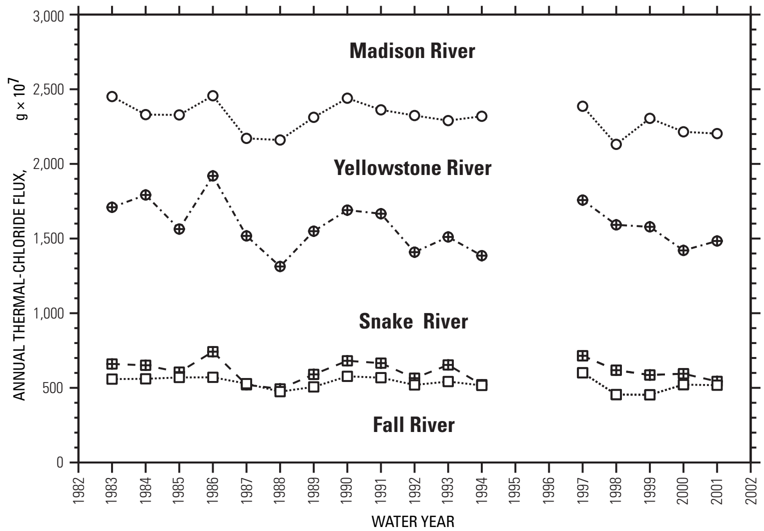

Figure 12. Graph of sums showing annual precipitation collected at five sites in the Park, annual discharges of the four rivers that drain the Park, and annual chloride fluxes of those four rivers.

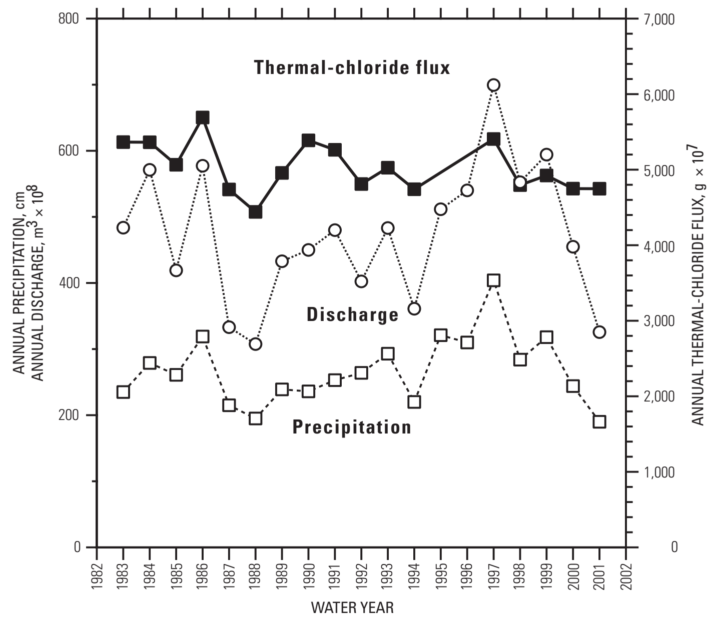

Table 11. Model data for the Yellowstone River.

[Column “Other hot springs” includes all thermal-water inflow other than Mammoth Hot Springs]

River input		Runoff		Mammoth Hot Springs		Other hot springs		Total	
cfs	Cl (ppm)	cfs	Cl (ppm)	cfs	Cl (ppm)	cfs	Cl (ppm)	cfs[a]	Cl (ppm)[b]
400	0.7	0	0.2	22	170	150	50	572	20.1
400	0.7	1,000	0.2	22.5	170	250	50	16,723	10.1
400	0.7	2,000	0.2	23	170	325	50	2,748	7.58
400	0.7	4,000	0.2	23.5	170	425	50	4,849	5.43
400	0.7	8,000	0.2	24	170	475	50	8,899	3.34
400	0.7	10,000	0.2	24.5	170	550	50	10,974	3.09
400	0.7	12,000	0.2	25	170	600	50	13,025	2.84
400	0.7	14,000	0.2	25.5	170	620	50	15,045	2.55
400	0.7	16,000	0.2	26	170	640	50	17,066	2.34
400	0.7	18,000	0.2	26.5	170	660	50	19,086	2.17
400	0.7	20,000	0.2	27	170	700	50	21,127	2.08

[a] Total cfs equals the sum of flows of River input, Runoff, Mammoth Hot Springs, and Other hot springs.

[b] Chloride concentration in the “Total cfs” calculated as follows:

[(column 1)(column 2)+(column3)(column 4)+(column 5)(column 6)+(column 7)(column 8)]/column 9.

5. The calculated seasonal variations in chloride flux in the rivers exiting the Park are believed to be related to changes in the discharge of thermal springs caused by changes in the height of the water table.

6. The effect of the height of the water table on hot-spring discharge has been observed for several thermal springs in the southwest area of Yellowstone Park. In effluent from these springs, the chloride concentration in the streams remained constant even though the discharge increased greatly during spring runoff.

7. Models have been constructed for the thermal- and non-thermal-water inflow to the Fall, Gardner, Madison, Snake, and Yellowstone Rivers above their stream gages. These models fit the observed chloride concentration–river discharge measurements and require that the amount of thermal-water inflow to each river vary seasonally, increasing during periods of snowmelt and decreasing during base flow of the rivers.

8. Although the year-by-year amount of total thermal chloride exiting the Park varies by as much as 20 percent, the average thermal-chloride flux for the 19 years of measurement, conducted over an interval of 21 years, shows a decline of 0.5 percent per year. The annual variation in thermal-chloride flux correlates with river discharge and with precipitation on the Park.

9. Correction of the total annual thermal-chloride flux for changes in river discharge from the Park results in corrected thermal-flux values that indicate a decline of 11 percent (0.5 percent/yr) from 1983 to 2003. This decline is mirrored by a decline in the frequency of eruptions of Old Faithful Geyser. Decreased output

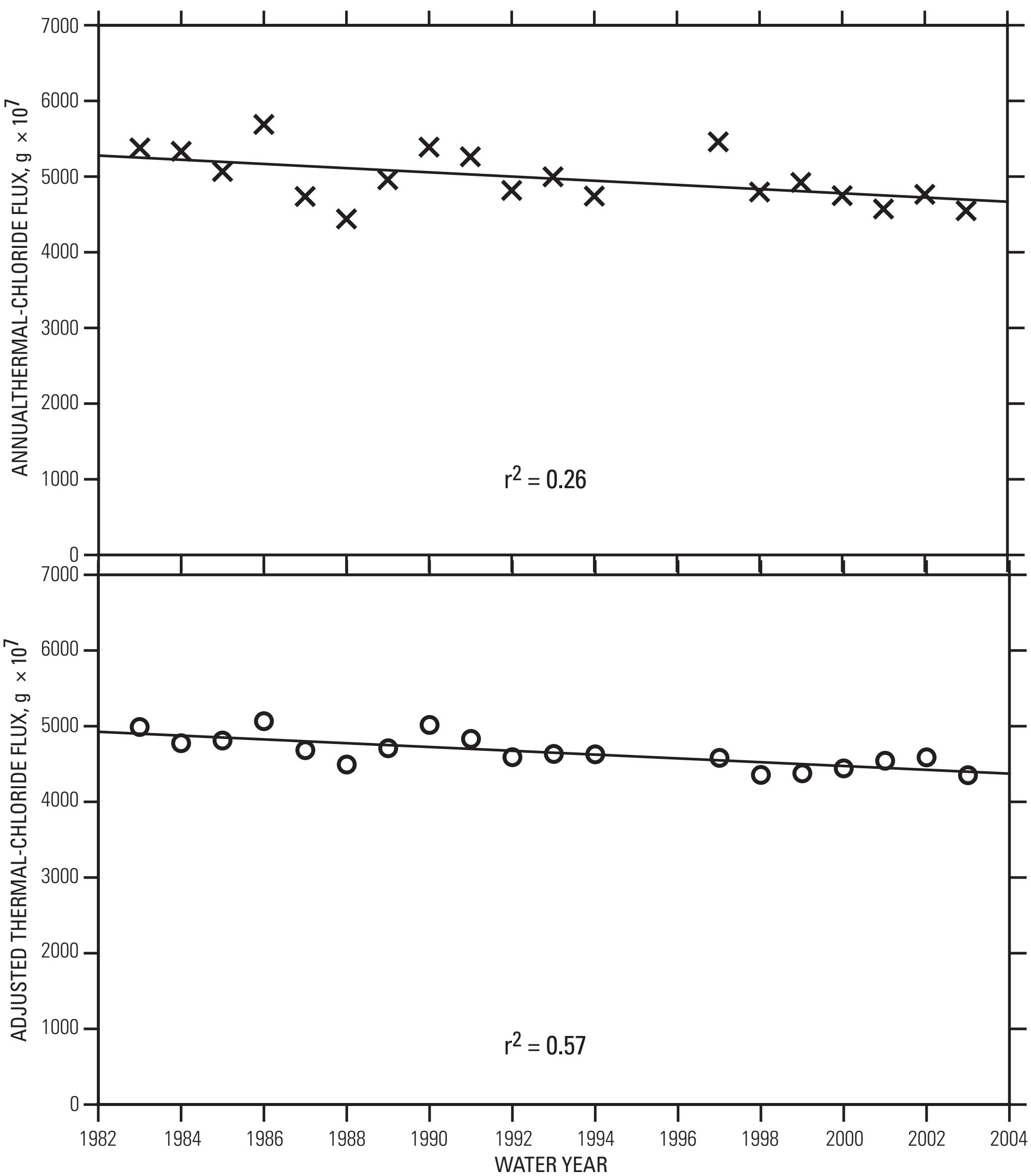

Figure 13. Graphs of the unadjusted and adjusted annual thermal-chloride flux out of Yellowstone Park for each water year.

of thermal water from the Yellowstone system may be a result of volcano-tectonic changes related to subsidence of the Yellowstone caldera.

10. The average annual total thermal-water discharge from Yellowstone is 130 million tons per year. This is equal to 96,000 acre-feet or a flow of 59,000 gallons per minute or 132 cubic feet per second.

11. The development of water, geothermal, gas, or oil resources adjacent to the Park would affect the water flux and pressure in the aquifer system beneath the Park. The aquifers are complex. In many places, thermal waters of very different chemical compositions exit in close proximity; consequently, it is difficult to predict the exact effect on individual thermal features by disturbances to either the hydrothermal system or to the cold-water recharge to hydrothermal aquifers. For this reason, we believe that, in addition to monitoring the rivers, it is necessary to monitor as many separate parts of the Yellowstone geothermal system as possible.

12. Because of the relation between chloride exiting the Park and climatic factors, it is necessary to accumulate continuous records, spanning at least 30 years, to properly assess natural changes in the hydrothermal system. Our measurement of chloride flux during the 21 years of record provides a minimal base from which to observe future disturbances to the Yellowstone hydrothermal system.

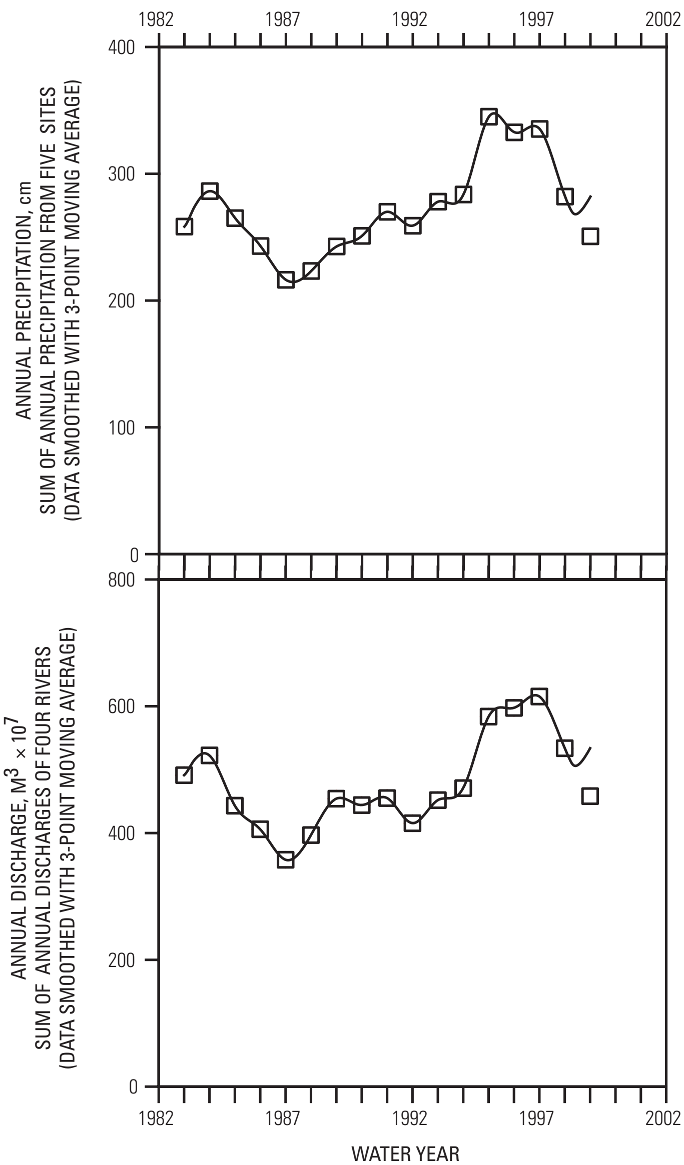

Figure 14. Graphs showing the annual precipitation and the annual discharge from the Park.

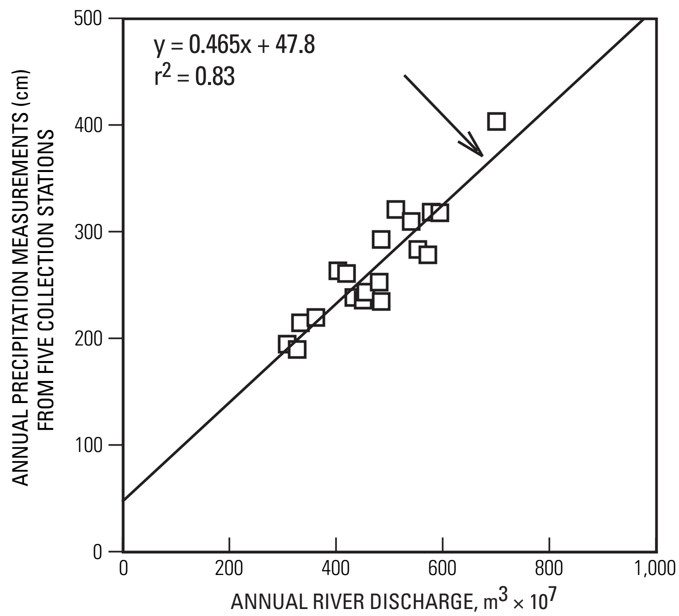

Figure 15. Graph of the sum of annual precipitation measurements from five measuring stations in Yellowstone Park versus the annual river discharge from the Park for the water years 1986–2001.

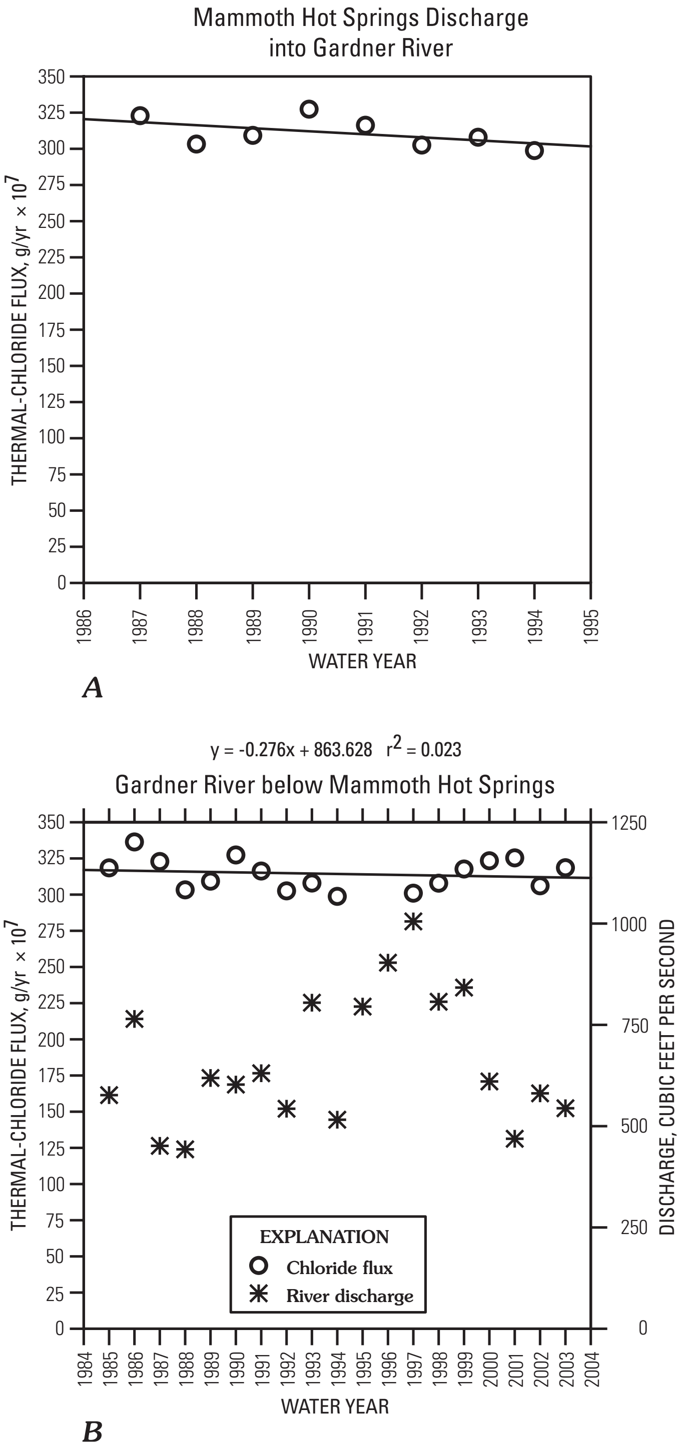

Figure 16. *A*, Graph of the annual thermal-chloride water discharge from Mammoth Hot Springs into the Gardner River. *B*, Annual thermal chloride discharge form Mammoth Hot Springs into the Gardner River for the water years 1985–2003. The annual discharge of the Gardner River is also shown.

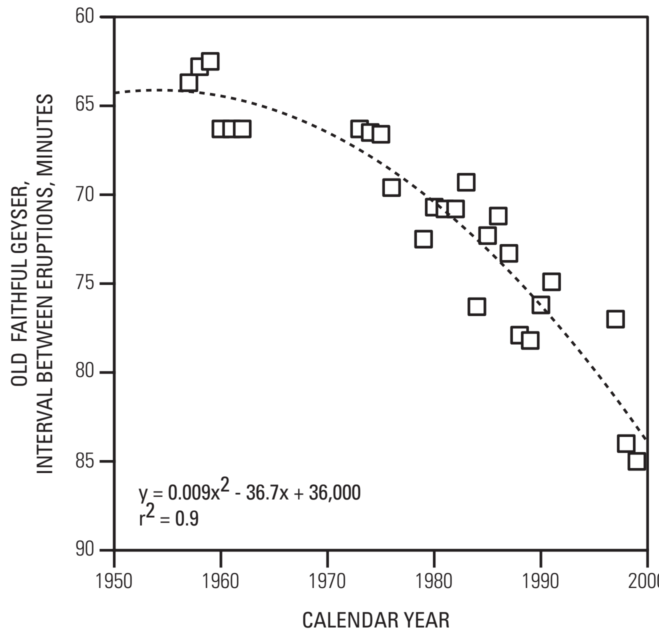

Figure 17. Graph of the annual average of the interval between eruptions of Old Faithful Geyser.

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